Astro 201; Project Set #3

due 3/09/2012

Problems focusing on bound-free and bound-bound cross-sections.

Where are the Accreting White Dwarfs Hiding?

The 2011 Nobel prize in Physics went to researchers using Type Ia supernovae (SNe Ia) as standard candles to discover the acceleration of the Universe. Embarrassingly, we still aren't sure exactly where these stellar explosions come from. Just about everyone agrees that SNe Ia are the thermonuclear explosion of a carbon-oxygen (C/O) white dwarf that has neared or exceeded the limiting Chandrasekhar mass ($\sim 1.4\ M_\odot$). How exactly the white dwarf (WD) is driven to a critical point, however, remains unclear.

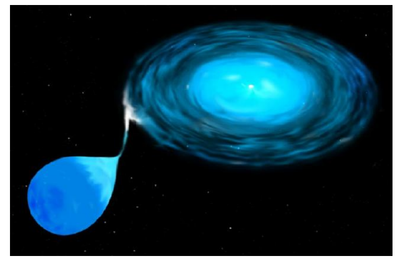

Figure 1: Artist's conception of single degenerate progenitor system. A compact white dwarf accretes mass (through a disk) from a non-degenerate companion star in Roche Lobe overflow.

For many years, the most popular progenitor model has been the *single degenerate scenario*, in which a C/O WD accretes matter gradually from a companion (either a main sequence star or a red giant). For certain accretion rates, the accreted hydrogen can burn stably to C/O on the WD surface. The mass of the C/O WD can therefore grow towards the Chandrasekhar mass, in which case the ignition of a thermonuclear runaway is inevitable.

A 2010 paper published by Gilfanov & Bogdan in Nature claimed to essentially rule out the single degenerate scenario as the main progenitor system in elliptical galaxies. They used x-ray observations of several nearby galaxies to try to directly constrain the emission from putative accreting WD progenitors. In this project, we try to understand their argument and look for ways to counter the paper's claims.

a) Say we have a single degenerate system in which a companion star dumps hydrogen on a $\sim 1\ M_\odot$ WD. Assume the energy released from burning H to C/O (around 10 MeV per H atom) is immediately radiated away. What is the maximum rate $\dot{M}$ (in solar masses per year) that the WD can accrete matter without violating the electron scattering Eddington limit?[1]. Assuming the mass transfer occurs at $\dot{M} \approx 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$, about how long will it take for the WD to gain the $\sim 0.4\ M_\odot$ needed to approach the Chandrasekhar mass?

[1] In fact, the flux mean opacity for these conditions is about a factor of 100 greater than electron scattering (due to bound-free and free-free absorption) in which case $L_{\mathrm{add}} \sim 10^{-5} M_\odot\ \mathrm{yr}^{-1}$. But detailed stellar evolution calculations suggest that the preferred stable accretion rates are sub-Eddington and indeed around $10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$.

b) Assume the radiation emitted from the WD surface has an approximately blackbody spectrum. At what energies (in eV) are most of the photons emitted from such accreting WDs? Several dozen sources radiating near these luminosities and energies have indeed been observed in our neighbor galaxy M31. They are called supersoft x-ray sources, and have been suggested to be the progenitors of Type Ia supernovae.

c) The observed rate of Type Ia supernovae in a typical galaxy is around 1 every 500 years. Assuming all of these supernovae come from accreting WDs, about how many supersoft sources will be shining at any given time in a typical galaxy? What would be the total luminosity $L_{\rm tot}$ emitted by supersoft sources in a galaxy?

d) These estimates suggest that we may be able to detect the emission from accreting WDs directly in a nearby galaxy. Unfortunately, we are going to have to deal with absorption by circumstellar and interstellar gas. Suppose that the interstellar medium has a density $n = 1$ cm^{-3} of diffuse neutral hydrogen spread around on a typical galactic length scale (~ 10 kpc). What is the order of magnitude optical depth in the continuum of this atomic hydrogen[2] when we try to observe the source at frequencies near the peak of its blackbody emission? How about if we try to observe at the much higher frequencies of the Chandra observatory (~ 1 keV)?

[2] For now, only worry about bound-free absorption by hydrogen. We'll get to absorption from metals in a second.

e) Given the optical depths you estimated, you will wisely choose to observe these galaxies using Chandra. However, since you will be looking at wavelengths away from the peak of the blackbody, the luminosity that can be detected in x-rays, $L_{\rm x}$, will only be a fraction of the total luminosity: $L_{\rm tot} = f L_{\rm x}$ where f is a bolometric correction. Estimate the value of f and predict the value of $L_{\rm x}$ that Chandra should observe for a typical galaxy, assuming a blackbody spectrum (and that all Type Ia come from accreting WDs).

Take the x-ray range of Chandra band to be from 0.1-10 keV.

f) Gilfanov & Bogdan compiled Chandra data to quantify the total x-ray luminosities of several nearby galaxies. They found (for example) a value of $L_{\rm x} = 6 \times 10^{37}$ ergs s^{-1} for the bulge of Andromeda (M31). Compare this to your predicted value for accreting WDs and confirm their conclusion that the requisite number of accreting WDs are not seen to explain all of SNe Ia.

Gilfanov & Bogdan claim that this result strongly rules out the single degenerated scenario as the main progenitor of SNe Ia[3]. I'm not totally convinced. Soft X-rays are fairly easily absorbed in diffuse gas, so perhaps the supersoft sources are simply obscured from view. In particular, it seems plausible that in a mass transferring system a small fraction of material may be blown off in a wind, either from the surface of the WD or the companion star. In this case, the WD may be enshrouded in a thin cloud of gas. But how strong a wind would we need to obscure a supersoft source?

[3] The main alternative progenitor system, which they promote in the article, is the *double degenerate scenario*, in which two white dwarfs in a binary system inspiral and merge violently

g) Assume the progenitor system blows a wind of hydrogen with solar metallicity which remains neutral. Calculate and plot the bound-free cross-section[4] in the Chandra wavelength range $0.1 - 1$ keV. You need only consider here the most abundant elements: H, He, C, O, Fe. What is a reasonable number for the total cross-section at 1 keV and which element(s) dominate?

[4] As an approximation, you can assume the K-shell absorption dominates and use the hydrogen-like relations. If you want more realistic cross-sections, code is provided on the website . Representative number abundances for solar composition are also provided on the website .

g) Find the wind mass loss rate,[5] $\dot{M}_\mathrm{w}$, that is required to reach an optical depth of $\tau \sim 3$ needed to attenuate the observed luminosity (in Chandra bands) by a factor of ~ 20? How does this wind rate compare to the accretion rate $\dot{M}_\mathrm{acc}$?

[5] Recall that for a wind with a constant mass loss rate the density surrounding the star is given by conservation of mass:

$$\rho_\mathrm{w}(r) = \frac{\dot{M}_\mathrm{w}}{4\pi v_w r^2} \tag{1}$$

where we might take the wind velocity v_w to be comparable to the escape velocity of the WD.

Comment: It therefore does not seem unreasonable that the accreting WDs indeed exist, but are being obscured by some fraction of material blown out in a wind. Binary evolution modelers have suggested scenarios in which mass loss from the systems does enshroud the supersoft sources, at least for a good fraction of their lifetime[6]. Of course, the energy being radiated from the WD surface has to go somewhere. We can see that most of the X-rays go into photoionizing hydrogen and other elements in the sounding gas. The subsequent recombination of the ions and the cascade to the ground state will release the energy largely as line radiation in the optical/UV. Some efforts to search for the H alpha emission of such an ionization nebula from an enshrouded accreting WD have been initiated.

[6] See, e.g, Hachisu et al., (2010)

Starlight Reflections on a Giant Planet

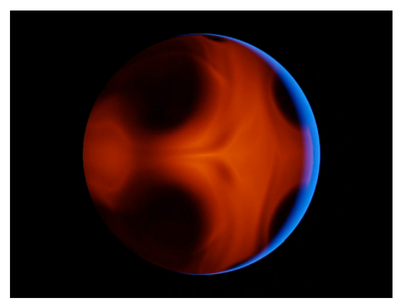

Figure 2: A simulated image of the exoplanet HD80606b, based on hydrodynamical simulations post-processed with radiative transfer calculations. For the paper Laughlin et al. (2009) .

Extra solar planets are too far away to image in detail, so we can let our theoretical imagination run wild. The simulated picture of a giant planet in Figure 2 shows a bright blue crescent of reflected starlight, atop the cherry red thermal glow of the heated planet.

The reflected starlight is clearly beautiful, but the actual color and visibility of the crescent will depend on the ratio of scattering to absorptive opacity in the exoplanet atmosphere. Just how shiny is a giant planet? Sudarsky et al.,2000 have performed detailed opacity and radiation transport calculations to determine the albedo (i.e., reflectivity) of jupiter like planets. In this project, we try to understand Sudarksy's results for one particular class of giant planets – those within around 0.05 AU of their star which have equilibrium temperatures of ~ 1500 K. He calls them class IV roasters (great name).

The atmospheres of giant planets are presumed to have essentially solar abundances, with the hydrogen primarily in molecular form. For class IV roasters, the primary scattering opacity in the optical is

Rayleigh scattering from hydrogen molecules. The primary absorptive opacity in the optical is from lines – in particular, the resonance lines[7] from alkali metals (i.e., sodium, potassium). Given the relatively high densities of exoplanet atmospheres, the width of these lines is determined not by Doppler broadening, but by pressure (aka collisional) broadening. This pressure broadening is caused by other particles perturbing the atoms, causing shifts in the frequency of bound-bound transitions. Although the full theory can become incredibly involved[8], a reasonable approximation for the shape of a pressure broadened line profile is just the familiar Lorentzian

[7] The term *resonance* line just signifies that the lower level of a line is the ground state. Burrows et al., 2000 worked out the theory of pressure broadened alkali metal lines and their relevance in exoplanet atmospheres.

[8] See e.g., 3.3.2 of the Stellar atmospheres book by Rutten.

$$\phi_\nu(\nu) = \frac{\Gamma/4\pi^2}{(\nu - \nu_0)^2 + (\Gamma/4\pi)^2} \tag{2}$$

The width in this case, however, is given by

$$\Gamma = \Gamma_\mathrm{n} + \Gamma_\mathrm{p} \tag{3}$$

where Γ_n is the natural line width and Γ_p is the pressure broadened line width. Roughly, $\Gamma_\mathrm{p} \sim 1/t_\mathrm{col}$ where t_col is the time between collisional perturbations of an atom. Burrows et al., 2000 estimate the pressure widths of alkali metal lines in these giant planets to be approximately $\Gamma_p \sim 10^{11}$ Hz.

a) The strongest resonance lines in this context are the two NaI lines at 5890 Å and 5896 Å (the famous sodium D lines!) and the two KI lines at 7665, 7699 Å. Look up the oscillator strengths of these four lines and estimate the cross-section at line center of each, assuming all sodium/potassium is neutral and in the ground state. Given that Na/K are only trace constituents of the atmosphere, it is best to give the cross-section per gas atom (e.g., the cross-section of a sodium atom times the solar number abundance of sodium).

The *single scattering albedo*, a_ss, is defined as the probability that a photon scatters in any given interaction with matter[9]

[9] Note that Sudarsky and others denote the single scattering albedo by σ, but I didn't want there to be any confusion with our notation for the cross-section. The albedo is a dimensionless quantity.

$$a_\mathrm{ss} = \frac{\sigma_\mathrm{scat}}{\sigma_\mathrm{scat} + \sigma_\mathrm{abs}} \tag{4}$$

A medium with $a_\mathrm{ss} = 0$ is purely absorbing, and one with $a_\mathrm{ss} = 1$ is purely reflecting.

b) Using the frequency dependent cross-section of Raleigh scattering and of the NaI D line[10] at 5890 Å, calculate and plot the single scattering albedo of a class IV roaster as a function of wavelength in the optical ($\sim 4000 - 8000$ Å). You can compare to the "isolated" model in Figure 7b of Sudarsky et al., to see if your simple model is in the right ballpark.

[10] If you want a better model, of course, you can include *all* of the resonance lines of both sodium and potassium. But to get an idea, one line will do.

Comment: In his figure 7, Sudarsky actually plots up the *spherical albedo*, A_s, of a class IV roaster, defined as the fraction of incident starlight that is reflected at all angles. Because incident photons can scatter multiple times in the atmosphere (and hence have multiple chances of being absorbed) the spherical albedo is generally less than the single scattering albedo. A full radiative transfer calculation is needed to determine the spherical albedo from the single-scattering albedo, which Sudarsky has done in his Figure 2.

Comment: To perform a real calculation of the single scattering albedo, we would have to determine what fraction of the alkali metals are indeed neutral and atomic. For hotter planets, the alkali metals may be partially ionized. For colder planets, the alkali metals may form molecules or condensates. If you look at other plots in Sudarsky et al., you can see that the formation of cloud decks (which are more reflective at all wavelengths) can have a big effect on the albedo of classes of giant planets. The theory of how atoms condense into clouds, however, is still highly uncertain.

Comment: Our calculations suggest that class IV roasters are fairly dark (more like coal than stainless steel). This is somewhat different than Jupiter itself, which has an albedo around 0.5. The albedo of some real giant planets have been constrained; for example the observations of Charbonneau et al., (1999) constrain the (geometric) albedo of one exoplanet to be < 0.3, fairly consistent with our findings.

Bonus (optional) question: Astro 201, The Real World

Depleted Uranium and the case of Stuart Dyson

ON A KECK RUN IN HAWAII, I read an article in the local tabloid about Stuart Dyson, a British soldier who died from a rare form of colon cancer. In 2009, a British coroners jury found that Dyson cancer was "...caused by or contributed to by his exposure to Depleted Uranium in the 1991 Gulf war." This conclusion is disputed by the British Ministry of Defense.

Depleted Uranium (DU) consists primarily of ^{238}U – the less useful isotope that is left over when the ^{235}U in natural uranium is extracted for reactor or weapons use. Given its high density, DU is used by the military for armor and armor piercing missiles. Some people have raised concerns that contamination of battlefields with DU can lead to health risks.

DU is a mild emitter of alpha radiation, but according to the standards established by the British Royal Society, the levels Dyson was exposed to were far too low to have affected his health. In the article, however, scientist Chris Busby puts forward a novel alternative theory: ingestion of DU could increase one's susceptibility to everyday background radiation. He argues that Dyson likely accidentally swallowed DU dust while cleaning equipment contaminated with the substance. Quoting from the article:

"A bit of DU trapped in [Dyson's] colon tissue, Busby calculated, *would absorb 201,000 times the background [gamma] radiation of living tissue*, and then release that energy into surrounding cells. As a result, those cells would get the equivalent of 70 years of normal background radiation in a single year, in addition to the damage caused by alpha particles from the uranium itself."

At first glance, the number quoted – 201,000 – sounds shockingly large, and I wondered whether this tabloid was really a serious publication. Armed with a little Astro201 knowledge, you should be able to evaluate (in your head even) whether Busby's claim is totally crazy or not.